AFRL-ML-WP-TP-2006-412

ADVANCED IMAGING OF HIDDEN DAMAGE UNDER AIRCRAFT COATINGS (PREPRINT)

James Blackshire and Adam Cooney

MARCH 2006

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)*	March 2006
2. REPORT TYPE	Conference Paper Preprint
3. DATES COVERED *(From - To)*	
4. TITLE AND SUBTITLE	ADVANCED IMAGING OF HIDDEN DAMAGE UNDER AIRCRAFT COATINGS (PREPRINT)
5a. CONTRACT NUMBER	In-house
5b. GRANT NUMBER	
5c. PROGRAM ELEMENT NUMBER	N/A
6. AUTHOR(S)	James Blackshire and Adam Cooney
5d. PROJECT NUMBER	N/A
5e. TASK NUMBER	N/A
5f. WORK UNIT NUMBER	N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Nondestructive Evaluation Branch (AFRL/MLLP) Metals, Ceramics and NDE Division Materials and Manufacturing Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson AFB, OH 45433-7750
8. PERFORMING ORGANIZATION REPORT NUMBER	AFRL-ML-WP-TP-2006-412
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	Materials and Manufacturing Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson AFB, OH 45433-7750
10. SPONSORING/MONITORING AGENCY ACRONYM(S)	AFRL-ML-WP
11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)	AFRL-ML-WP-TP-2006-412
12. DISTRIBUTION/AVAILABILITY STATEMENT	Approved for public release; distribution is unlimited.
13. SUPPLEMENTARY NOTES	This work has been submitted to the Proceedings of the 2006 Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring, published by SPIE. This is a work of the U.S. Government and is not subject to copyright protection in the United States. PAO Case Number: AFRL/WS 06-0265, 13 Feb 2006. This paper contains color.
14. ABSTRACT	The paper describes the evaluation of several advanced imaging methods for detecting damage hidden under aircraft coating systems. The specific imaging technologies include thermographic imaging, mid-infrared imaging, and terahertz imaging which are all relatively mature and widely known throughout the scientific community.
15. SUBJECT TERMS	Hidden Damage, Aerospace Coatings, Nondestructive Evaluation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			James Blackshire
Unclassified	Unclassified	Unclassified	SAR	18	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Advanced Imaging of Hidden Damage under Aircraft Coatings

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ABSTRACT

The external coating systems of nearly all military aircraft are stripped to bare metal during programmed depot maintenance cycles. This paint stripping process has become cost prohibitive in recent years, and is expected to continue to be a major and escalating problem for the sustainment of an aging Air Force fleet. Although a number of competing factors come into play, the key reason behind current paint stripping practices is centered on requirements for visual inspection of the aircraft structure to determine if corrosion and/or fatigue damage is present. In recent years, a number of advancements have been made in the area of nondestructive evaluation (NDE) that provide new inspection capabilities for aircraft skins without the requirement for protective coating removal. In this effort, several advanced imaging methods are evaluated for hidden damage detection and quantification through typical aircraft coating systems. A number of measurement examples are provided for engineered and realistic aircraft reference standards with variations in coating type, coating thickness, hidden damage type, and component complexity being considered. A comparison of measurement sensitivity, resolution, area coverage, ease-of-use, quantitative assessment, data processing requirements, and inspection speed are also made. It is anticipated that the use of one or more of these advanced NDE methods for thru-paint inspections will provide an enabling capability for long-life coating systems and condition based maintenance practices resulting in significant reductions in hazardous waste generation, dramatic cost savings, and enhanced readiness levels for a wide variety of Air Force systems.

Keywords: Structural Health Monitoring, Piezo Wafer Active Sensors, Displacement-Field Imaging

1. INTRODUCTION

The detection and repair of corrosion and crack damage in aerospace structures currently costs the U.S. Air Force in excess of $800 million/year to treat [1]. Much of this cost is due to scheduled maintenance activities, which often require the stripping of paint from an aircraft, or the complete disassembly of component parts for inspection. These rather aggressive maintenance procedures are needed to ensure that hidden damage is not present in structural components, which could compromise the structural integrity of the aircraft if left unchecked. Current standard practice used during depot maintenance activities involve the complete stripping of an aircraft coating system to permit visual inspection of the outer skin of the aircraft. If visual indications of damage are found, further maintenance action is taken to assess the extent and level of damage and to accomplish repair. This may involve the use of more sophisticated NDE methods for quantitative damage assessment, additional component disassembly, or both. Current inspection and maintenance processes are time-consuming and inefficient, resulting in an aircraft system being out of service from months to over a year. The availability of a quick and reliable nondestructive inspection method for detecting and characterizing hidden damage under an aerospace coating system would go a long way in reducing some of these maintenance costs, and ultimately improving flight safety and aircraft readiness.

A significant amount of technology development has occurred within the last 10 years with the goal of producing advanced nondestructive inspection methods capable of detecting and quantifying hidden damage in aircraft structures [2-4]. This work has focused on developing innovative methods for inspecting an aircraft structure without disassembling component parts and/or without stripping the paint. Numerous methods have been developed and tested for a wide variety of hidden damage detection problems. Many of these methods involve extensions and improvements to the traditional five nondestructive evaluation methods: ultrasound, eddy current, magnetic penetrant, fluorescent

penetrant, and radiography. Several additional methods have also been developed which have taken whole new approaches to nondestructive inspection. Thermography, for example, has transitioned in recent years from a laboratory system to an extremely practical and capable inspection method for a wide variety of damage detection problems.

In this current effort, an assessment of state-of-the-art inspection methods for imaging hidden damage beneath aerospace coatings is undertaken. Several advanced imaging methods are evaluated for hidden damage detection and quantification through typical aircraft coating systems. A number of measurement examples are provided for engineered and realistic aircraft reference standards with variations in coating type, coating thickness, hidden damage type, and component complexity being considered. A comparison of measurement sensitivity, resolution, area coverage, ease-of-use, quantitative assessment, data processing requirements, and inspection speed are also made. It is anticipated that the use of one or more of these advanced NDE methods for thru-paint inspections will provide an enabling capability for long-life coating systems and condition based maintenance practices resulting in significant reductions in hazardous waste generation, dramatic cost savings, and enhanced readiness levels for a wide variety of Air Force systems.

2. IMAGING HIDDEN DAMAGE THROUGH AEROSPACE COATINGS

Aerospace coatings used on the outer skin of an aircraft function primarily as a protective measure against environmental effects for the underlying aircraft structure. For most of the aging aircraft in the Air Force fleet, the coating involves the use of a multi-layered protective layer for the metal subsurface, where active protection against corrosion processes is a major functional feature. The entire coating system is typically thin (2-5 mils or 50-125 microns), made up of a conversion coat/chromate-based primer layer, and a durable topcoat layer. The conversion coat/primer layers are applied directly to the material substrate, and help with adhesion and chemical resistance to corrosion activity. The topcoat layer is applied over the primer layer providing an environmental durable, color pigmented outer layer.

A typical aerospace coating system blocks the transmission of visible radiation (and UV radiation) primarily through the pigmentation in the topcoat layer. This results in the coating being opaque for visible inspections, and unless corrosion or crack features penetrate through the coating in some manner (e.g. exfoliation, coating bulges, discoloration, tears or rips in the coating), visible inspections will not be effective. Regarding the other major NDE methods, however, the existence of a aerospace coating typically induces only minor effects on the ability of the NDE method to perform an inspection on the substrate material. Aerospace coatings are typically not conductive or magnetic in nature, which minimizes effects on electromagnetic techniques like eddy current and microwave NDE. The elastic properties of the coating also have minimal effect on ultrasound measurements, and in fact can actually provide a benefit for contact transducer coupling. Coating density is also not a significant problem for radiographic measurements. Thermal energy absorption and heat transfer affects are also manageable for thermography measurements, and like the ultrasound NDE case, the presence of the coating can actually benefit the thermography measurement process by more efficient heat absorption into the material system with the coating present. In all cases, the major effects of the coating would be to add noise to the NDE measurement which can affect detection sensitivity levels, and reduce spatial resolution levels thru various energy scattering processes. Of note, however, is potential effects due to thickening coating levels, coating degradation and uniformity variations, and inspecting through specialized coatings.

The following sections describe the leading NDE methodologies for inspecting through aerospace coatings, with a particular emphasis on recent advances that would impact and improve the inspection process.

2.1 Visual Imaging Methods

Visual inspections are performed whenever the inspection surface is visible by sight or by using visual enhancing equipment (e.g. digital camera, magnifying lens, or borescope), and by its very nature provides an whole-field imaging capability for detecting damage. Visual inspections are typically simple, fast, easy to accomplish, and usually very low in cost. The inspection can be done on exposed surface of the aircraft and also on internal areas that can be made accessible by removing access panels or equipment. Figure 1a depicts a de-painted aircraft in depot maintenance activity and Figure 1b provides a close-up view of a lap-seam region that has been visually inspected. An important point to be made is that of the shear size and complexity of the inspection problem, even with the coating removed (Figure 1a).

Physically accessing the various surfaces for inspection can also pose a problem, along with variations in surface quality, lighting conditions, and geometric complexity of the inspection surface. The lack of a permanent recording of the inspection, limited damage quantification potential, and issues related to inspector variability are two additional problems.

a) b)

Fig. 1. a) De-painted aircraft in depot maintenance facility, and b) close-up of visually-inspected lap-seam region which showed visible evidence of corrosion.

The close-up image of a lap-seam region depicted in Figure 1b shows a number of fasteners and the lap region which are of critical concern for structural integrity, and which are also prone to crack and corrosion problems. Visual inspections are capable of detecting very minor levels of surface corrosion (~0.1% material loss levels) as a surface roughness variation or discoloration, and surface cracks approaching 10s of microns in length. Records of visual inspections can be augmented and recorded with cameras and video devices. In addition, visual inspections can be augmented with various imaging hardware using flexible or rigid borescopes, magnification systems, dye and fluorescent penetrant systems, and structured lighting systems. An interesting camera-based inspection method called 'D-sight' involves using a shallow-angle incidence viewing angle which can enhance detection sensitivities for surface cracks and corrosion relative to simple visual inspection [5]. The inability of visual inspections to perform through coatings is its major drawback.

2.2 Ultrasonic Imaging Methods

Ultrasonic NDE is one of the most commonly used and oldest techniques for assessing the structural integrity of a component part, and for detecting cracks and corrosion in aerospace structures. It involves the insertion of mechanical vibration energy into a material substrate, which propagates as elastic waves through the material. The internal structure of the host material can be assessed by monitoring how the elastic waves propagate through the material, and by characterizing any elastic scattering events that are caused, for example, by localized cracks and corrosion. Both contact and non-contact approaches have been used to insert and detect the mechanical energy into the material substrate, with piezo-electric transducers being the overwhelming source and receiver elements in traditional ultrasonic NDE systems. Noncontact ultrasound measurement approaches utilizing air-couple transducers, EMATs, and laser-based ultrasound have also shown significant promise and progress recently.

Contact transducers typically require a coupling fluid to efficiently transfer the mechanical energy into the structure. Raster-scanned versions of each of the ultrasound approaches described above provide area inspection coverage and imaging capabilities, but are time consuming, somewhat complicated to setup and operate, and typically require a highly trained inspector. Laser-based systems are also typically expensive and somewhat fragile.

Resolution and sensitivity levels have a strong dependence on the frequency and energy levels used, along with the type of analysis processing that is done. Corrosion material loss level sensitivities of 5-10% have been reported with spatial resolutions approaching 10s of microns for megahertz transducer frequencies. Laser ultrasound measurements are

typically optical diffraction limited (1-5 microns) for spatial resolution limits which are due to the use of a focused laser beam as the probe. Material loss level measurements have recently reported below 1% in lap-joint specimens [6].

The possibility of making whole-field, imaging measurements using ultrasound energy has also recently been reported by Lasser et. al. [7], and Bar-Cohen et. al. [8]. By combining ultrasonic array transducer designs with real-time, charge-coupled device technologies, the possibility of imaging ultrasound inspections has become a possibility. The devices operate in a manner similar to a camcorder device, providing frame rate (30 fps) measurement capabilities. The size of the inspection area is still rather small (~1cm^2), but the possibility of making whole-field, wide-area ultrasound inspections through coatings is very appealing. The ability to provide quantitative damage measurements, and to inspect multi-layered, complex structures are advantages of the method.

2.3 Electromagnetic Imaging Methods

Eddy current NDE is a major method of choice for detecting hidden corrosion in aircraft structures. In the eddy current technique a probe coil (or coils) generates a localized ac electromagnetic field in a part and detects the part's response due to the induced eddy currents. Defects such as corrosion or cracks perturb the eddy current field and are subsequently picked up as an impedance and phase variation in the probe circuit. Variations of the basic eddy current approach include giant magneto resistive (GMR), magnetoresistive (MR), pulsed eddy current (PEC), multi-frequency eddy current (MFEC), and remote-field eddy current (RFEC). The primary differences between the different measurement approaches involve probe configurations, drive frequencies, and analysis methodologies. In all cases, the affect of the coating system on detecting corrosion and crack damage beneath the coating system is minimal. Dramatic improvements in detecting damage in thick, metallic, multi-layered structures, and complex geometry structures (e.g. beneath fastener heads) has driven recent development efforts. Pulsed eddy current in particular, has shown dramatic advances in its robustness to variations in geometry, paint thickness, rivet heads, surface warping, and liftoff, which should allow this technology to be a credible field technique in the future. Raster-scanning of the eddy current probe provides a method for imaging through coatings, but as with the scanning ultrasound methods, they involve time consuming, complicated measurement procedures, which typically require a highly trained inspector. Detection sensitivity and spatial resolution levels do not typically approach ultrasound sensing levels, but the ability to detect damage at significant depths, and non-contact inspection provide advantages.

Similar to the ultrasound camera concept, distributed electromagnetic sensors using electromagnetic sensing principles have recently been described and reported in the literature [9,10]. Two concepts in particular, the Meandering Winding Magnetometer (MWM) and the Magneto Optic Imager (MOI) have shown significant potential in recent years. The size of the inspection area is significantly larger than the ultrasound camera systems (~50cm^2 vs ~1cm^2), with reports of making whole-field, wide-area inspections of hidden cracks and corrosion through coatings reported recently [9,10]. The ability to provide quantitative damage measurements tends to be more limited, but the advantage of inspecting deep, multi-layered, complex structures has been proven.

Microwave, mm-wave, and terahertz NDE methods represent additional electromagnetic-based NDE methods that have only recently found more widespread appeal as an inspection tool. Both coaxial and rectangular waveguide approaches have been used for microwave and mm-wave sensing systems, while terahertz systems have utilized femtosecond laser-pumped modulation of microantennas and nonlinear crystals. More recently, the use of semiconductor heterostructures for generating and detecting terahertz energy have shown promise. In all three cases, the high-frequency electromagnetic signals can easily penetrate typical aerospace coatings permitting the inspection of the substrate material for damage through the reflection or transmission of the electromagnetic signal. The level of signal reflection/transmission is dependent on the dielectric properties of the material where corrosion and crack features disturb the electromagnetic return signal. The use of evanescent microwave probes with very sharp tips have provided resolution levels approaching 1 micron, while open-ended, rectangular waveguides have shown enhanced sensitivity levels. Imaging is currently limited to raster-scanning of microwave, mm-wave, and terahertz energies/probes, but the recent developments in imaging array technologies appear promising.

2.4 Radiographic Imaging Methods

Radiography is another traditional NDE technique that has seen significant technological advances in recent years. These advances have improved resolution levels [11], and can provide fully three-dimensional imaging of materials

through computer tomographic means [12]. Although different types and levels of energy beams can be used as a probe source, X-rays are most frequently used for most materials. The x-ray energy interacts with the material and primarily provides a measure of material density in a thru-transmission measurement sense. Subtle variations in material composition can also be measured by using a dual-energy comparative measurement approach. Hidden corrosion is measured as a change in the thru-transmission material density level, and provides a local measurement of material loss.

Recent developments in the area of digital radiography, backscatter x-ray, and reverse-geometry x-ray have provided innovative methods for providing fast, efficient, and portable x-ray measurement capabilities. The backscatter x-ray method, in particular, measures the reflected radiation from the component part, thereby requiring only single-sided access to the structure. Large-area, real-time inspections are now possible with portable digital radiography systems, but hazardous radiation conditions still limit widespread use.

2.5 Thermographic Imaging Methods

Thermographic imaging is a relatively new NDE technology, that uses thermal differences between a material defect and its local surroundings as a non-contact and full-field NDE measurement tool. Infrared cameras with higher sensitivities and resolutions are currently helping to transition the technology from a novelty to a comprehensive and quantitative NDI measurement tool. An embedded defect (corrosion pit or void) has a thermal emissivity that is different from the substrate material. In a passive thermography measurement the material surface will naturally radiate, scatter, and reflect infrared energy that can be imaged by a thermal camera. Differences in thermal emissivity and thermal diffusion will be imaged as variations in image brightness, allowing damage to be detected and characterized.

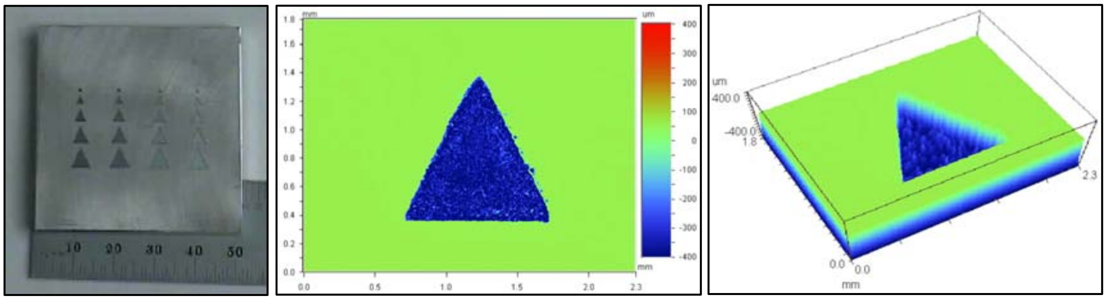
In certain instances, thermographic measurements can be made in a spectral bandpass window that allows the infrared energy to transmit through a coating layer to probe the material substrate underneath [13]. This in fact is the case for typical Air Force primer/topcoat paint combinations, which have a spectral transmission window in the 3-5 micron wavelength range. By using a mid-wave infrared camera sensitive to 3-5 micron thermal energies, and/or using bandpass filters in that wavelength range, hidden damage in the substrate material can be imaged directly through the paint.

Active heating of the material can also be use to image the material surface and subsurface regions below a coating with increased sensitivity. The basic concept of active thermographic NDT involves the input of heat energy into the surface of a solid, where the heat transfer and emissivity is affected by internal flaws such as disbonds, voids or inclusions. In pulsed thermography, a short burst of heat energy (typically from a quartz lamp) is used to heat the surface of the sample, and an infrared camera is used to detect changes in the surface temperature as the sample cools. An infrared camera captures the radiating heat, where a computer can be used to analyzes the cooling behavior of each point on the sample and creates an image of the coated surface or subsurface structure. Large, near-surface flaws are typically detectable using simple heat systems, while deeper, multi-layer regions typically require further computer enhancement. The increased use of thermal imaging for nondestructive evaluation provides one of the simplest and fastest means to inspect large areas of interest with minimal effort and cost.

3. EXAMPLES OF NDE IMAGING THROUGH COATINGS

A series of engineered coated corrosion standards were created so that a side-by-side comparison of the five NDE techniques could be done. The standards consisted of precision-laser-cut features, and pitting corrosion created in Al-2024-T3 aluminum substrate coupons. The corrosion features were created with variations is surface extent between 50μm to 5mm, and depths ranging from 10μm to 1mm. This represented material thickness loss levels ranging from 0.1% to 25%. Images of the hidden corrosion features were then obtained by each of the NDE techniques, and assessments of the material loss sensitivity, signal-to-noise ratio levels, and resolving powers were made.

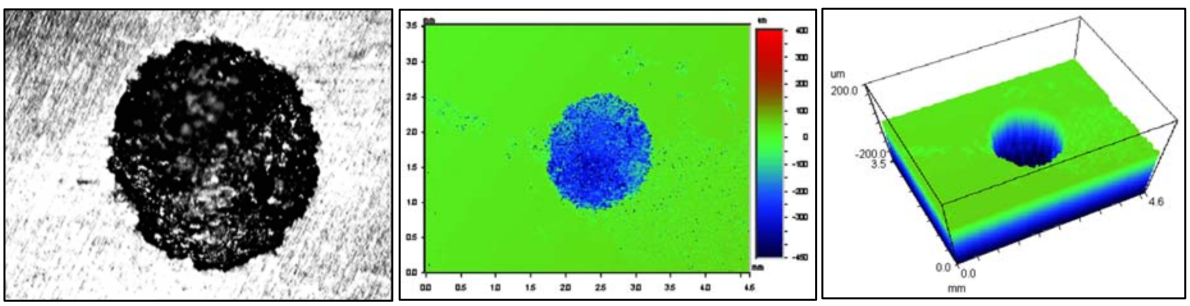
The precision-laser-machined samples consisted of recessed triangle cutouts ranging in size from 1mm to 5mm on a side, and 25μm to 1mm in depth. Figure 2a provides a digital image of one of the samples, along with a detailed topographic measurement (Figures 2b and 2c) of one of the triangle features obtained using a white-light interference microscope system. The topographic measurements provided a detailed and absolute measure of the microscopic features of the defect site, which could later be compared directly to each of the NDE measurements. The use of a triangle-shaped cutout allowed resolution estimates to be made using the triangle's sharp-edge features.



a) b) c)

Fig. 2. a) Laser-machined triangle sample, b) topographic measurements of one of the triangles, and c) 3-d topographic measurement of the triangle.

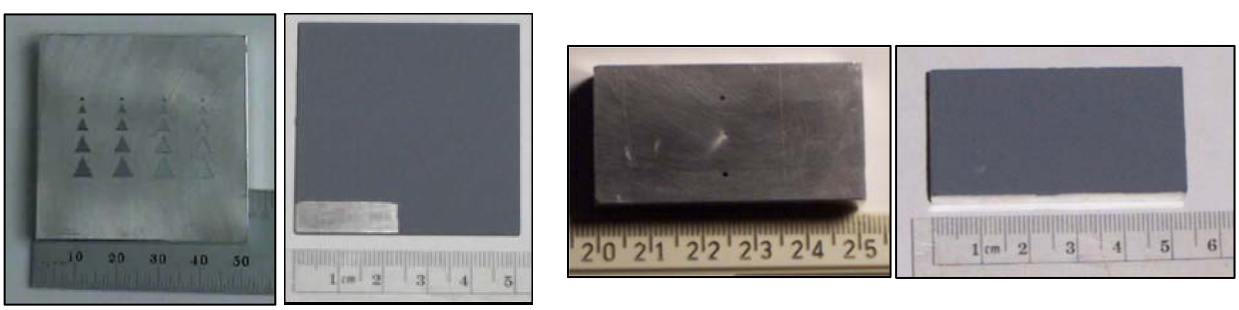
While the laser-machined triangles did provide an approximation of the material loss associated with corrosion, it was important to work with actual corrosion sites as well. Corrosion pitting was introduced into aluminum substrate coupons using a commercial electrochemical treatment system. A simple masking procedure was used to isolate the pit location and to limit its maximum surface extent. The system allowed reasonable control over the generation of a variety of pit sizes and depth in the micron to millimeter range. Figure 3 provides digital and topographic measurements made on one of the samples.



a) b) c)

Fig. 3. a) Electro-chemically generated corrosion feature, b) topographic measurements of the corrosion, and c) 3-d topographic measurement of the corrosion.

After the engineered corrosion samples had been created, they were coated with a standard Air Force primer and topcoat paint layer. A set of examples for the laser-machined triangle and electro-chemical pitting corrosion coupons is provided in Figure 4a and 4b, respectively, for before- and after-paint coating. The coating layer was 2.5-3.0 mils thick and had a diffuse, somewhat rough surface character (rms roughness of ~1 μm).



a) b)

Fig. 4. Engineered corrosion samples before- and after-paint application. a) Laser-machined triangle sample, and b) pitting corrosion sample.

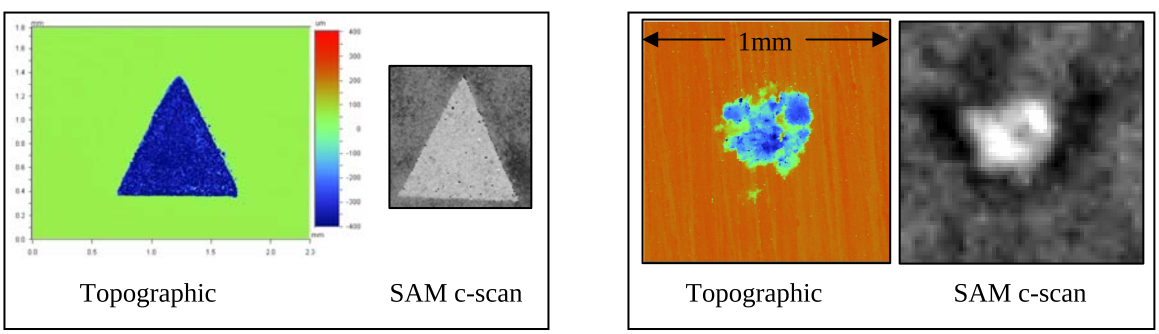
3.1 Ultrasound Imaging Measurements

A Scanning Acoustic Microscope (SAM) system and its immersion water tank was used to measure the coated corrosion standards. Even though this is not the type of system that would be used in the field, it did provide a basic capability assessment for the ultrasound method. The ultrasonic transducer used in the system had a nominal center frequency of 50 MHz and a focal length of 6.5 mm. The transducer design was optimized to achieve a narrow, almost single cycle pulse, which allowed a clear time-separation of the reflections from the various reflection interfaces (e.g. water/coating and coating/substrate). By applying the appropriate time-gating and probe standoff positions, the substrate/paint interface could be probed effectively. A set of c-scan images (Figure 5) provides further evidence of this, where the water/topcoat interface and paint/substrate interfaces provide significantly different information regarding the coating/substrate features. In effect, the water/topcoat image is providing exclusive information about the coating, while the coating/substrate image is providing information about the substrate, embedded corrosion in the substrate, and coating/substrate bond variations. The corrosion pitting site is easily seen in the coating/substrate image as a white feature on the dark background. A topographic reference image of the corrosion site is provided in Figure 5c for comparison to the ultrasound measurement made through the coating shown in Figure 5b.

a) b) c)

Fig. 5. Ultrasound measurements of coated corrosion sample. a) ultrasound signal analysis set for top of coating layer, b) ultrasound signal analysis set for coating/substrate interface layer, and c) topographic reference image taken before coating was applied.

The use of engineered corrosion samples allowed the direct one-to-one comparison of the SAM images with the actual topographic features of the hidden corrosion site. Figure 6 provides examples of this for one of the triangle samples (Figure 6a), and one of the electrochemically pitted corrosion samples (Figure 6b). An extremely good match is seen between both sets of c-scan images obtained with the SAM system, and the topographic characteristics of the defect sites. In both cases, the engineered hidden corrosion site appears as a bright intensity against a dark background.



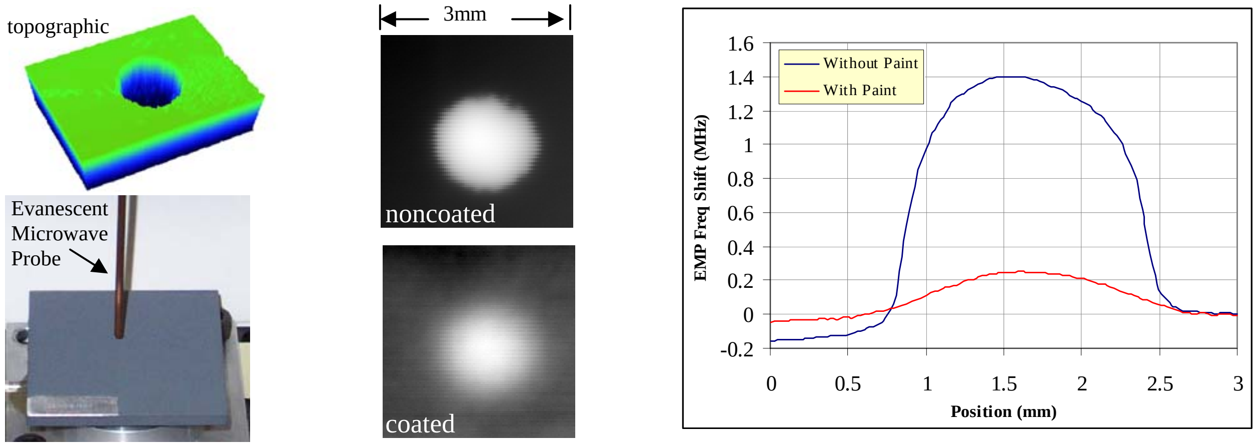
a) b)

Fig. 6. Ultrasound measurements of coated reference and corrosion samples. a) laser-etched triangle feature, and b) corrosion feature.

3.2 Microwave Probe Imaging Measurements

Microwave measurements were made using a coaxial microwave probe in an evanescent mode configuration. The evanescent microwave field is developed using a sharp inverted probe tip at the end of the coaxial waveguide channel.

The basic technique monitors the resonant interaction of a material substrate with a localized microwave signal in the low gigahertz range, where resonant frequency shifts and power loss measurements are used to characterize the material’s conductivity, dielectric response, and topography. By raster-scanning the probe relative to the material’s surface, a high resolution image can be generated with spatial resolutions in the 1-100µm range. Figure 7a depicts a coated corrosion sample being scanned by the microwave probe along with a topographic plot of the hidden corrosion feature. Figure 7b and 7c provide measurement results for the corrosion pit with and without the coating present. A loss of resolution and reduction in signal level can be seen in the measurement results for the coated sample relative to the noncoated sample.

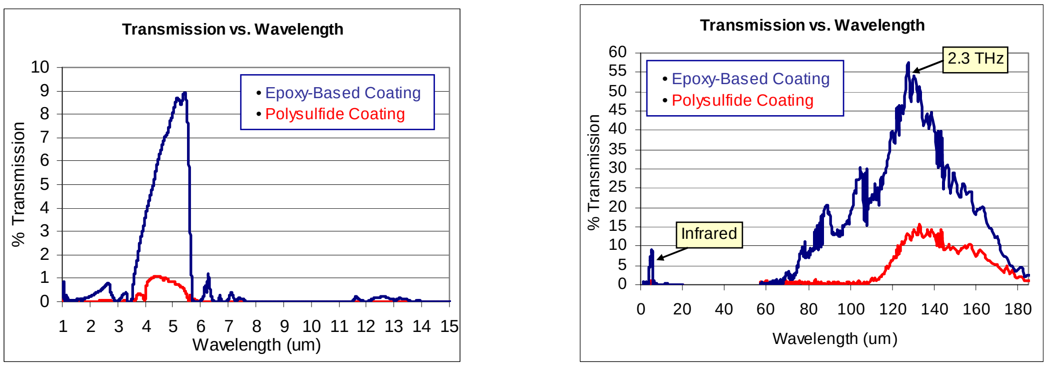


a) b) c)

Fig. 7. a) Evanescent microwave probe system measuring of coated corrosion pit sample, b) microwave images taken with and without coating layer present, c) comparison of response signals across corrosion pit location with and without coating present.

3.3 Passive Thermography Imaging Measurements

The ability to capture a full-field image of a hidden damage under a simple paint layer is very appealing, and passive thermography provides an attractive means for accomplishing this. Current state-of-the-art, focal-plane array infrared camera systems have excellent temperature sensitivities (25mK) and resolution capabilities (30 µm). Infrared camera manufactures have also customized the spectral response characteristics of their systems to cover the near-IR to far-IR. An Indigo Merlin MWIR camera was used in this effort to image hidden corrosion features under paint. Its spectral response characteristics are optimized for the 3-5 µm range, which makes it ideal for imaging through aerospace coatings. Figure 8a provides a spectral transmission curve for two types of aerospace coatings involving an epoxy-based coating system and a polysulfide coating system. Figure 8b provides an additional set of transmission spectra for energy in the terahertz portion of the electromagnetic spectrum compared with the infrared spectrum results.



a) b)

Fig. 8. a) Infrared transmission spectra for epoxy-based and polysulfide coatings, and b) comparison of infrared and terahertz transmission spectra.

The results in Figure 8 indicate that for the same coating material, a high transmission (50% for the polyurethane and 18% for the polysulfide) could be obtained in the far-IR (THz) region compared to the relatively low transmission (8.5% for the polyurethane and 1.5% for the polysulfide) in the mid-IR region. The development and availability of terahertz detectors and sources is progessing in recent years, but is still several years off. Even with the <10% transmission levels, mid-infrared imaging has recently been shown to be capable of imaging through aerospace coatings. Figure 9 provides a set of images taken with the thermal camera system operating in a completely passive mode. The defect sites again appear as bright image features against a dark background. The defect sites correspond to a 1mm/side x 250µm deep triangle (Figure 9a), and two pitting corrosion samples (Figures 9b and 9c) that were ~ 200µm – 300µm in overall size, and 30µm - 50µm deep. The resolution, signal-to-noise, and image contrast levels were excellent when compared to the topographic features of the defect sites.

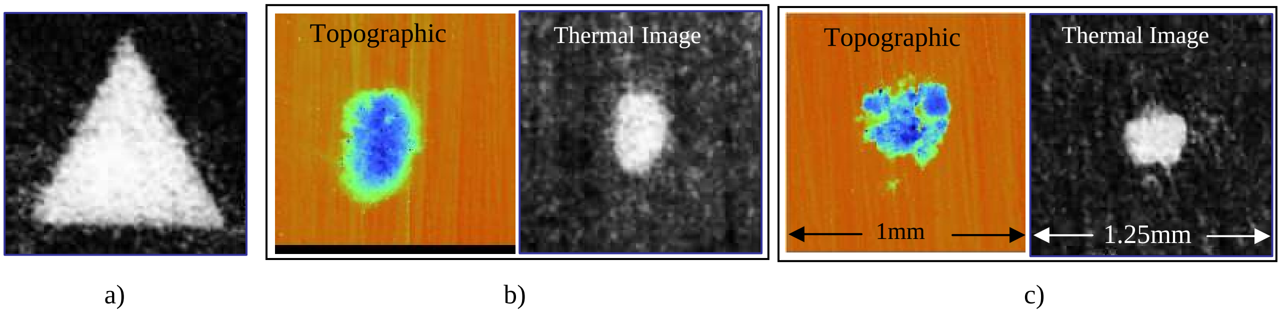


Fig. 9. Passive thermography measurements of coated reference and corrosion samples. a) laser-etched triangle feature, b) corrosion feature #1, and c) corrosion feature #2.

4. NDE IMAGING THROUGH COATINGS: CAPABILITIES AND LIMITATIONS

It is clear that there are many different NDE methods that have the capability for measuring damage hidden below an aerospace coating system. Figure 10 provides hidden damage measurement examples for five different methods including immersion ultrasound, laser ultrasound, passive thermography, film radiography and evanescent microwave NDE. Each measurement image was obtained for the same engineered triangle feature which was hidden below a standard epoxy-based, 3-mil thick aerospace coating layer. Regarding the need for a practical inspection capability for large aerospace structures the additional properties of sensitivity, resolution, area coverage, ease-of-use, quantitative assessment, data processing requirements, and inspection speed also need to be considered. These properties are considered in the following subsections.

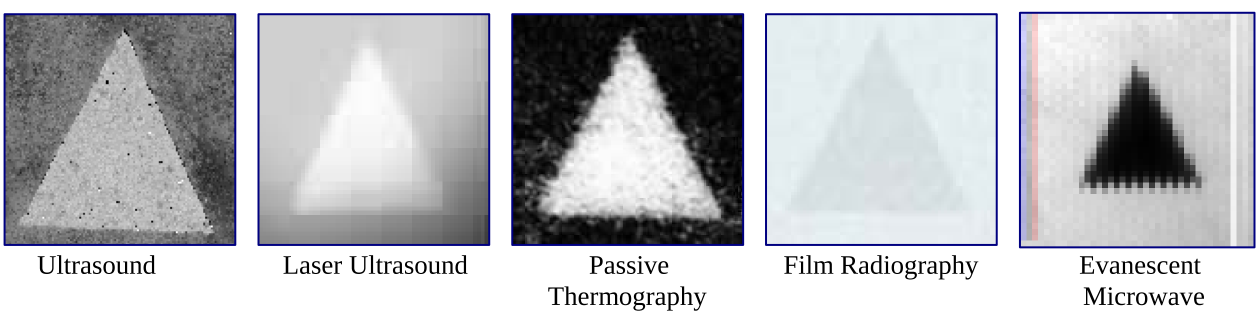


Fig. 10. Detection of hidden engineered corrosion feature below a standard aerospace coating system using five nondestructive inspection methodologies.

4.1 Sensitivity

Traditionally, measurements of corrosion using NDE techniques have been focused on evaluating corrosion material loss levels and crack length as precisely and with as much sensitivity as possible. Current NDE measurement systems with a capability for measuring material losses with a sensitivity 5% or less and crack lengths of several hundred

microns are considered to be good. The laser-machined triangle measurements presented in Figures 10 correspond to a 260μm deep feature in a 4mm thick sample coupon, which corresponds to a material loss level of 6.5%. The corrosion pitting measurement results presented in Figures 5-9, however, were much shallower (40μm to 50μm deep), and were in a much thicker sample coupon (1cm thick), which places material loss sensitivity levels at 0.1% to 2%, which is considered excellent. Coating type, coating thickness, and geometric complexity will tend to degrade sensitivity levels.

4.2 Resolution

For raster-scanned measurement systems, resolution levels will be determined primarily by the probe interaction footprint and the step-size of the scan. For imaging methods, resolution will be determined by the various imaging system parameters such as aperture, focusing conditions, and sensing array parameters. In most cases, the resolution limits of the NDE method will be in the 10's of micron range to mm levels. Excellent resolution capabilities, for example, are seen in the immersion ultrasound and thermographic results presented in Figures 5-10 above. Coating type, coating thickness, and geometric complexity again tend to reduce resolution levels as depicted in the microwave measurements depicted in Figure 7.

4.3 Area Coverage

The only full-field measurement method studied directly in this present effort involved passive thermography. The possibility of utilizing imaging ultrasound, imaging eddy-current methods, and active thermography provide additional methods which show significant promise for the future. Wide-area coverage is perhaps the most important capability with regard to offering a potential replacement for visual inspection methods currently in use. Thermal imaging cameras offer the most immediate possibility for fast, simple, camera-based inspections for thru-coating inspection which mimics visual inspections. The limited transmission levels of 1-8%, however, will become an issue with problematic coatings and thicker coatings. Terahertz imaging systems are several years off, but offer another wide-area imaging method for thru-coating measurements as shown in Figure 8.

4.4 Quantitative Assessment

With the use of adequate calibration procedures, techniques involving ultrasound, eddy current, and radiographic measurements have the ability to provide quantitative assessments of material loss level and crack length. Imaging methods involving visible and thermal energies provide spatial indications of surface area and crack length, but are limited with regard to quantifying depth information and material loss levels.

4.5 Ease-of-Use

Camera-based, full-field imaging methods hold the best promise for providing a simple and effective NDE method that can compete with current visual inspection systems. Raster-scanned methods involving ultrasound, eddy current, and microwave probes require additional setup, calibration, and data analysis processing.

4.6 Data Processing/Analysis Requirements

Passive thermal imaging provides the simplest means for thru-coating measurements, requiring minimal data processing for interpretation. Ultrasound, eddy-current, microwave measurements in contrast provide much more information at the cost of requiring significant data analysis and data processing procedures. This limits their

4.7 Measurement Speed

Raster-scanned measurements are typically limited to measurements of several points per second which limits measurement speeds from minutes to hours. System setup is also time-consuming relative to direct imaging methods which adds time to the measurement process.

5. CONCLUSIONS

The potential use of a wide variety of nondestructive inspection methods are currently available for through-coating damage detection. With respect to replacing visual inspections with coatings being removed, more work is needed to make the NDE methods simpler to implement, and more capable. The movement of traditional inspection methods to full-field imaging modalities is encouraging and will help to bring fast, reliable, and efficient inspection capabilities to

the field that will begin to compete with current visual inspection methods. Further improvements in detection sensitivity levels, resolution levels, handling geometric component complexities, deeper flaw detection levels, and quantification of damage is progressing steadily. The results showed the potential for future NDE systems to provide a quick and reliable capability for detecting and characterizing hidden damage under paint, which should go a long way in reducing aircraft maintenance costs and improving flight safety.

ACKNOWLEDGEMENTS

The authors would like to thank and acknowledge the Center for Materials Diagnostics at the University of Dayton for use of the near-field scanning interferometry system, and the WYCO surface profilometry system, without which this research would not have been made possible. Mr. Ed Porter and Mr. Dan Daniels prepared the digitized radiographic and CT images respectively. Authors appreciate contributions of both engineers to the study.

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